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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No.

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
Biswaroop	Mukherjee	Ottawa, CANADA
Bill	Gage	Stittsville, CANADA
Jerry	Chow	Kanata, CANADA

☐ *Additional inventors are being named on the ___ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

PAIRWISE INDEPENDENT SCHEDULING FOR NODES WITH A SINGLE PARAMETERIZABLE RADIO IN A WIRELESS NETWORK

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ENCLOSED APPLICATION PARTS *(check all that apply)*

☑ Specification *Number of Pages* 10

☑ Drawing(s) *Number of Sheets* 1

☐ Application Data Sheet. See 37 CFR 1.76

☐ CD(s), Number

☐ Other (specify)

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☐ Applicant claims small entity status. See 37 CFR 1.27.

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Respectfully submitted,

SIGNATURE [signature]

Date 04/28/04

TYPED or PRINTED NAME Benjamin S. Withrow

REGISTRATION NO. *(if appropriate)* 40,876

TELEPHONE 919-654-4520

Docket Number: 7000-365-P

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

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UNITED STATES PROVISIONAL PATENT APPLICATION

Biswaroop Mukherjee
Bill Gage
Jerry Chow
INVENTORS

PAIRWISE INDEPENDENT SCHEDULING FOR NODES WITH A SINGLE PARAMETERIZABLE RADIO IN A WIRELESS NETWORK

Withrow & Terranova, P.L.L.C.
P.O. Box 1287
Cary, NC 27512
(919) 654-4520

Docket No. 7000-365-P

PAIRWISE INDEPENDENT SCHEDULING FOR NODES WITH A SINGLE PARAMETERIZABLE RADIO IN A WIRELESS NETWORK

Background of the Invention

[0001] A network where each node shares a single communication resource to exchange data between its (possibly many) neighbors needs to determine when and how long should it communicate with each of its neighbors so that there is a minimum of collision. This determination of timing and sequence of communication events is referred to here as the scheduling problem. As an instance of such a network we consider a mesh network where each node has one radio and is expected to exchange data with several other nodes by multiplexing its radio, the problem is for each node to create a schedule that determines when and for how long to exchange data with its neighbors to avoid collision.

Qualifiers

[0002] Widespread nodes: One reason to create a wireless mesh network is to provide widespread coverage by means of wireless nodes that form the backhaul infrastructure. This is an attempt to extend the model of the model of wired node access points where backhaul is over the wired network. In order to be successful the nodes are expected to be spread out in space, with the obvious requirement that at least one node connected to the existing mesh be able to communicate with a new outlying node. So the scheduling solution cannot rely on all the nodes being able to "hear" schedule announcements from one source.

[0003] Directional radios: Directional radios allow the medium to be separated as transmissions on a beam towards one node does not overlap (significantly) and thus affect with a beam from the same radio on a different beam, or that of a beam possibly from a pair of nearby nodes. However this may prevent the use of broadcasts that are used by the 802.11 MAC for scheduling, or such broadcasts would negate some of the benefits of directional radios.

[0004] The method proposed does not require scheduling signals to be duplicated – each node signals each of its neighbors exclusively, thereby exploiting directional nature of the antenna.

[0005] Independent clocks and synchronization: One of the fundamental problems scheduling in time is that the notion of time in different entities, even if they have the same hardware, is non-uniform and varies with time. Furthermore, there isn't one channel or direct link through which all the nodes can obtain consistent timing and relaying this information over the nodes themselves is likely to be expensive. So following a pre-determined schedule will fail because of the relative drift of time in nodes. Some form of periodic synchronization of clocks may be required to deal with the drift between nodes. However due to different degrees of variations if one node synchronizes with one neighbor by adjusting its clock, it may in fact be de-synchronizing with another neighbor. Many approaches have been attempted to resolve these problems, including the following.

[0006] Centralized scheduling: The 802.11 MAC [1] has its own scheduling algorithms. In the BSS mode of the algorithm, the Hybrid Control Point function in the access point determines the schedule based on the requests sent in by the stations and conveys this back to them. Each station then follows this schedule until the next time they receive another schedule. This method is only useful when all the stations can hear the schedules being broadcast by the AP. In a network using direction radios, such schemes will fail because the broadcasts will not reach nodes that are out of range or are not along the beam containing the transmitted schedules. The method described here however does not depend upon a single controller or upon a broadcast mode of operation. In fact, as long as a new node can communicate with one of the nodes already in the system, the new node can be incorporated and will be a part of the distributed schedule being maintained thorough the network.

[0007] Decentralized scheduling: In 802.11 IBSS mode and in the Distributed Control Function mode of a BSS, each node independently attempts to send data after sensing its channel. This strategy allows networks with widely separated

nodes as there is no requirement for the broadcast of a central schedule. As the number of nodes and traffic increases on the medium, nodes that sense the medium to be busy will perform exponential back-off required for such random access of a shared medium and thus the throughput of the system will be much lower when compared to the method proposed here.

[0008] Arbitration: Arbitration schemes that attempt to provide coordination such that two neighbors can exchange data when they have packets in their queues, such as RTS/CTS signaling may alleviate some of the overhead of exponential back-off. RTS/CTS schemes have been adapted to directional antennas [2][3], where parts or all of the signaling is done using directional antenna in order to try to encourage multiple simultaneous non-interfering transmissions [4]. However arbitration schemes like RTS/CTS incur costs that grow with the number of nodes in the network and setting up synchronization when a data packet to be sent out on a link arrives, may take an arbitrary amount of time depending upon the traffic serviced by the neighbors. The method proposed here is constant cost (independent of the number of nodes and their distribution) and provides bounded response time and does not require any back-off. In addition the proposed mechanism exploits the separation of media provided by directional antenna (and multiplexing other parameters) to obviate the RTS/CTS synchronization with a schedule that is guaranteed to be such that at no time sending receiving pair non-distinct. Given properly separated media this property of the schedule allows for interference less function without RTS/CTS or back-off overhead.

[0009] Hierarchical: A master-slave relation like the BSS mode can be extended such that master's slave can be a master to other slaves, thereby forming a hierarchical tree of nodes [5]. Such a system can prevent back-off because schedules for each node will be determined by its corresponding master. However, the drawback of such a system is that the root of the whole tree or roots of sub-trees become points of failure, making all the subtending nodes vulnerable. In addition, propagating the schedule from the root to the leaves is likely to be cumbersome and susceptible to clock errors, where the time

reference in all the nodes will need to be guaranteed to be within bounds for the schedule to work. Otherwise if a node's time reference deviates, it will, for instance, start sending data when it's not supposed to and disrupt the system. The method described here has no masters that define the schedule for slaves. Indeed each node is independent to infer radio parameters to use from its environment and create its own schedule. This way, failure in the schedule of a node only affects its own schedule and the interaction with its neighbors, while interactions of the neighbors with their other peers are not affected. In addition, two peers keep the notion of their relative time within bounds, which incurs much less overhead than all nodes synchronizing to a wall clock determined by the root of the tree.

[0010] The method described here does not require any node to ever change its own notion of time, hence avoiding de-synchronization with other nodes as described above. It relies on relative time intervals, using an arbitrary and coarse-grained notion of clock frequency ("ticks per second"), and attempts to bound the variation in such interval with each of its neighbors independently of others by periodically redetermining a fresh set of intervals, thereby avoiding drift.

Summary of the Invention

[0011] The present invention shows a non-interfering schedule of an ad hoc network of nodes with parameterizable radio, which can be achieved by nodes that independently coordinate to form time varying communicating pairs (that are guaranteed to be unique) by local message exchange. The present invention as described herein is a novel distributed algorithm that creates local schedules in such a way that the local schedule in each node and its corresponding data transmissions over the shared medium are non-interfering with the schedules of other nodes and their transmissions. The algorithm works by isolating pairs of nodes as communicating units and maintaining uniqueness of such pairs in time. This along with parameterized radio ensures that non-interfering node pairs in proximity as well as throughout the network can use the shared medium to

communicate at the same time without interfering with each other, obviate previously proposed collision avoidance schemes.

[0012] The novelty of this method is the creation of node pairs, which are isolated using parameterized radio to simultaneously communicate over the shared medium and therefore do not need any other access control. In this way, it is expected that the nodes will be able to achieve high parallelism in data exchange, as well as maintaining robust and scalable scheduling.

[0013] Those skilled in the art will appreciate the scope of the present invention and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

Detailed Description of the Preferred Embodiments

[0014] The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the invention and illustrate the best mode of practicing the invention. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the invention and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure.

[0015] Pairwise independent scheduling exploits radios that are parameterizable to be non-interfering (e.g. operate in different frequencies and/or use beamforming antenna to localize their area of interference) to provide a robust, scalable (in the number of nodes and distance) and adaptive distributed scheduling mechanism at a low, fixed overhead cost of periodic coordination between neighboring node pairs.

Local scheduling to achieve robust inexpensive global scheduling

[0016] Instead of creating a schedule that encompasses all nodes at once (e.g. a global schedule), or a cascading schedule determined by a local master for its slaves, the method described here decouples the network's schedule into independent schedules for neighboring node pairs. Each node is responsible for

its own schedule. The synchronization is between two neighbors and is independent of their synchronization with other neighbors. This allows nodes to form pairs that can communicate at the same time without collisions by exploiting the separation of the shared media afforded parameterizable radio. The schedule created is guaranteed to be such that at any time each sender-receiver pair is globally distinct in its constituent nodes from all other pairs, and by choosing suitable parameters for its radio each pair is made locally non-colliding (the same parameters can be used by other nodes that may be far away). The exact algorithm to choose such parameters is not described here.

<u>Independence from shared clocks purely interval based scheduling</u>

[0017] Pairwise independence in scheduling allows each node to maintain its own clock independently i.e., it doesn't need to change it's own clock to match the clock of any other node (e.g. master). The schedule of communication between two nodes works on time intervals, not external time or wall clocks. The start time and duration of the intervals are negotiated between the neighbors as required. They then independently count down to the event and if their clocks are within error bounds useful information exchange can occur. Note that this interval is such that two neighbors can synchronize to without altering their wall clocks. Each node also ensures that its previous commitments are not changed (due to any external synchronization or reset of wall clocks,) thereby atomically ensuring that subsequent commitments do not conflict with previous ones, thus providing non-preemptive scheduling.

[0018] We use the following model to define the problem setting. There exists a set of nodes in the network $N = \{n_0, n_1, ..., n_k\}$. Each node n_i can determine a set of it's neighbors, i.e. nodes that are first degree peers $N_{Bi} = \{n_p, n_q, ..\}$ that it can communicate directly with. Upon initialization a node will attempt to gather information about its peers and try to communicate with them in order to create its neighbor set. The specifics of such a method to discover neighbors is beyond scope. We assume that after a node pair has established themselves as neighbors (i.e. added themselves to the others neighbor set) the two will be able

to communicate for some time sufficient to exchange a small constant number of messages.

[0019] Time in a node is a non-decreasing counter, which can be read at any instant in a variable T. This counter can be viewed as slotted, where a time slot is an atomic time unit for the scheduler (i.e. a singular useful function can be accomplished in a time slot). A node's schedule is then a set of contiguous slots $SC = \{S_0, S_1, S_2, ..., S_k\} = \{t_0, t_1, t_2 ..., \}$, where t_0 is the start of the next slot as well as the end of the present slot; t_1 is the end of slot 0 and start of slot 1 and so on and slot S_i occurs before S_j implies that the corresponding start time values are such that $t_i < t_j$. Furthermore the schedule only has entries for the finite future (i.e., t_k is a finite value of the time counter) and the current value of T is never greater than $t0$. We also assume that a time constant of D units is known to be the upper bound for the drift in the clocks of the nodes.

[0020] Each node creates a schedule similar to the one above, such that, if in a node n_i the schedule for any time instant indicates that it is to communicate with a neighbor n_j then there is a corresponding entry for the same time instant in the schedule of n_j that indicates that it is to communicate with n_i. If time was denoted in the schedule in terms of contiguous discrete intervals then the requirement above can be extended such that if in a node n_i, the schedule for a time slot indicates that it is to communicate with a neighbor n_j then there is a corresponding entry for the same time slot in the schedule of n_j that indicates that it is to communicate with ni. Such time slots are represented as $S_i = \{t_i, n_i\}$, where t_i is its start time i.e., the value of T at which slot i is to start, and n_i is the corresponding neighbor or null for the times when there are no neighbor to communicate with.

[0021] When a new node starts, its SC will have slots with null neighbors. As the nodes discover neighbors and exchange messages with them (to begin with this need not be coordinated in time, e.g. random overlap) they reserve slots in each others schedules, allowing subsequent scheduled negotiations to be coordinated in time. The duration of a slot that is negotiated is proportional to the time that is required to exchange the buffered data destined for a neighbor. Since

the slot will begin a finite amount of time after the exchange to reserve the slot, a function that computes the expected data to be exchanged using the present queue length and history is used at the time of negotiating the slot size.

[0022] A message exchange sequence is used to negotiate the free slots and the time required for the nodes to drain their data. Negotiation between two nodes *A* and *B* is as follows. First, *A* sends *B*, T_A the time it needs to drain its buffered packets destined for *B* and F_A, that is a self of slots that is free at that time in node *A*. *B* performs similar computation to calculate T_B and F_B, and upon the receipt of *A*'s message it calculates *T*, the total time required by both *A* and *B* to drain their data buffers. It then matches the free slots of both *A* and *B*, to find common time intervals, i.e. slots (or parts of slots), from F_A and F_B until all the free slots of one node are exhausted or all of *T* has been booked. The resulting set of slots, B_{AB}, is said to be the set of booked slots for that negotiation and is conveyed back to node A so that it can book those slots in its schedule as well. The process has been depicted in Figure 1.

[0023] Since B_{AB} is computed out of F_A and F_B and only one booking occurs and completes at any given time, the bookings can be guaranteed serialized and thus to not conflict with any existing bookings. Note that in order to convey free slots the nodes need to use relative time, because they have free running independent clocks. Relative time is calculated by a common event, referred to as the *reference point* of the negotiation. One such reference point is the reception of *A*'s message at *B* and if the MAC layer provides message acknowledgement the reference points for both *A* and *B* can be very close together in terms of absolute time. Therefore, F_A and B_{AB} are both denoted in terms of relative time, which can be calculated as time since the previous reference point. The further the reference point of *B* is from that of *A*, the more error will occur in the times booked at both ends. Also note that in the above discussion instead of sending time T_A the amount of data can be directly communicated, if the other end can compute some time equivalent of it to calculate the total amount of time that needs to be booked in the free slots.

[0024] A given node can repeat this process periodically with all of its neighbors to continue to communicate with them. The message exchange above can be interleaved with user data exchange (e.g. as a preamble). However, scheduled communication with a neighbor may be lost if no booking for a future slot exists in the upcoming schedule. In order to prevent this from happening, the exchange to book future slots books, will in the absence of any data to be exchanged, book small slots that will be purely for the sake of completing another negotiation and thereby keeping the neighbor in the schedule.

[0025] The mechanism above allows nodes to schedule data exchange with its neighbors, who will in turn be able to relay data to their neighbors and so forth. In this way, a large network can globally exchange data, hop-by-hop, by using a completely locally determined scheduler, where locality is a node and its direction neighbors. This method is independent of any global clocks and does not require communication with any entity other than direct neighbors.

[0026] Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present invention. All such improvements and modifications are considered within the scope of the concepts disclosed herein.

References

The following items are incorporated herein by reference in their entireties:

1. IEEE, IEEE Proposed Standard 802.11e (DRAFT), "Medium Access Control (MAC) Enhancements for Quality of Service (QoS)".
2. Y.B. Ko *et al.*, "Medium Access Control Protocols Using Directional Antennas in Ad Hoc Networks," *IEEE INFOCOM 2000*, March, 2000.
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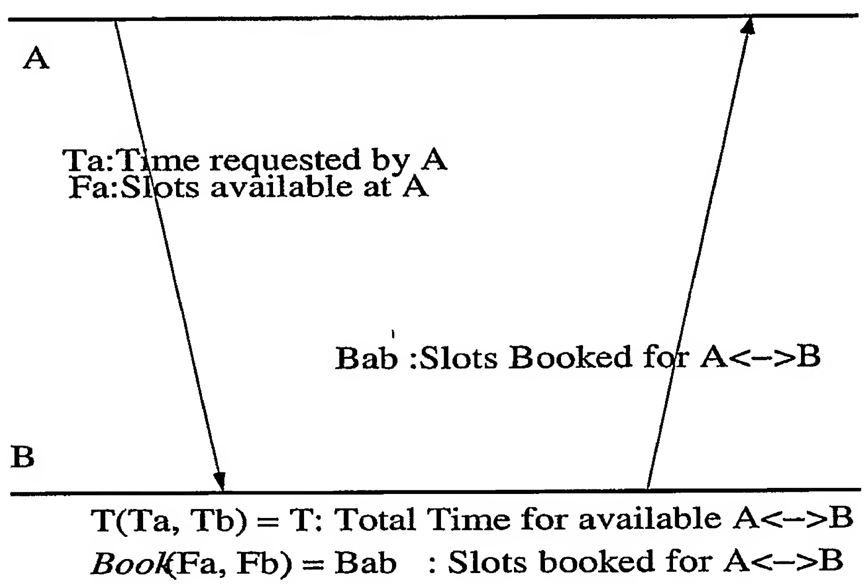
A
Ta:Time requested by A
Fa:Slots available at A
Bab :Slots Booked for A<–>B
B
T(Ta, Tb) = T: Total Time for available A<–>B
Book(Fa, Fb) = Bab : Slots booked for A<–>B

Figure 1